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Design of Advanced Neuroscience Platform

Wentai Liu, Moo Sung Chae, Zhi Yang and Hyunchul Kim

***Abstract*— This paper presents the design of versatile platform for advanced neuroscience on the high-level brain functions and neural prostheses. The platform enables researchers to record and stimulate brain activities of multiple free behaving animals wirelessly. The platform consists of three major functional blocks of neural interface, wireless communication system, and neural signal processing software, which of each has fundamental challenges to be overcome. Ultra wideband communication system makes it possible to transmit a large amount of data produced by high-density microelectrode wirelessly and miniaturize the entire system so that it can be implanted or carried by animals. Multiple access capability is achieved by a sophisticated communication protocol optimized for biomedical applications. Noise is one of the most important factors affecting the design of the neural interface and neural signal processing technique to reduce the noise is presented. Prototype chips were fabricated to verify the feasibility of the platform and test results are shown as well.**

***Index Terms*—Neuroscience, neural prostheses, platform, ultra wideband, neural signal processing, and noise**

I. Introduction

METHODOLOGIES based on recording and stimulation through microelectrode arrays are widely used to record and stimulate the nervous system both *in-vivo* and *in-vitro*. However, there is a rapidly growing need for neuroscience platform, which can perform chronic recording and stimulation of neural tissue in a completely wireless fashion together with powerful signal processing software to facilitate the analysis of the chronic recording data. This platform technology is required for identifying and understanding the underlying mechanisms of the complex nervous system and developing neuroprosthetics to treat debilitating chronic neurological disorders such as deafness, blindness, spinal cord injury, depression, and several brain-related diseases. Many of the basic neuroscience questions remain unresolved due to a lack of our ability to simultaneously interface with a large population of neurons in awake, unrestrained behaving animals in a chronic setting. Such a technology would help explore and reveal the mechanisms of short-term and long-term memory formation and retention, the substrate of consciousness, sensorimotor integration, and cortical plasticity. This technology will also improve the understanding and underlying mechanisms of neurological disorders such as Parkinson's disease, migraine, epilepsy, Alzheimer's disease, tinnitus, schizophrenia, and depression. Finally, this technology will enable advance neural prostheses.

However, during the development of the platform technology for those studies on high-level functions, fundamental challenges and difficulties are faced. First, the neural interface, which is composed of microelectrode arrays and microelectronics, is preferred to operate in completely wireless fashion because tethering wires to connect the neural interface to external units inhibit the free movement of biological objects. However, currently available data telemetry link is seriously limited by communication bandwidth, resulting in a small number of recording channels that can be monitored simultaneously. Second, research on high-level functions of the brain is often related with the interaction between multiple biological objects. This demands multiple access capability to the neural interfaces, which requires an appropriate communication protocol that should be embedded in the platform. Third, application based signal processing algorithms to decode information and infer biologic functions are critical. These algorithms should be effective and reliable to recover the encoded information; they are expected to analyze data in an unsupervised manner, which avoids frequent user intervene and operated independently and intelligently.

There have been a lot of researches to realize a wireless neural interface [1-5] but a versatile platform which can support the study on high-level brain activity has not been reported yet. Most systems are incapable of high-density, lossless and simultaneous wireless recording mainly due to the limited bandwidth of the telemetry. Moreover, multiple-access capability for high-level study on interaction has not been realized yet.

This paper presents the design of platform which will meet a rapidly growing need in the neuroscience community, which can perform chronic recording and stimulation of neural tissue in a completely wireless fashion with a powerful signal processing software to facilitate and enhance the analysis of the data and ultimately realize a closed-loop control system for implantable neural prostheses.

The paper is organized as follows. Section II discusses the detailed challenging requirements of the platform and solutions to overcome. Section III focuses the implementation and test results.

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Wentai Liu, Moo Sung Chae, Zhi Yang, and Hyunchul Kim are with the Department of Electrical Engineering of University of California at Santa Cruz, Santa Cruz, CA 95064 USA (phone: 831-459-1856; fax: 831-459-4829; e-mail: wentai@ soe.ucsc.edu).

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II. System Requirements and Architecture

The platform consists of three major components: a neural interface for chronic recording and stimulation, a high-bandwidth, bi-directional communication system with multiple access capability, and neural signal processing software for data analysis. The block diagram of the proposed neural interface platform is depicted in Fig. 1. As shown in Fig. 1, the platform can also be divided into two different interfaces: wireless neural interfaces, which are implanted on the biological object and an external user interface, which is outside the biological object. The wireless neural interface is composed of the neural interface that is composed of high-density microelectrode arrays (MEAs) and a local communication unit. The user interface consists of central communication unit and neural signal processing software. Each component has challenging design issues and should be optimized according to the constraints imposed by the nature of the applications.

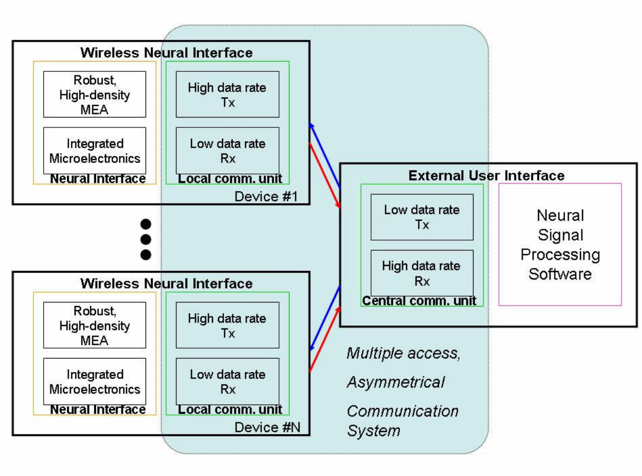


Fig. 1. Block diagram of the proposed platform.

A. Neural Interface

Noise, which comes from various sources, is of great importance in the design of platform because it eventually determines the quality of the recorded signal, and therefore the actual performance of the platform. The recording environment is usually very noise and the signal amplitude is very small resulting in difficult in spike sorting, which is essential for the analysis of the data and the design of neural prostheses. Fig. 2 depicts the major noise sources that contribute to the total noise of the system. Different noise source has different impact and methods to reduce. For example, various types of low-noise amplifiers including chopper amplifiers [6] have been proposed to minimize the noise from the electronics and several different kinds of electrodes have been developed to reduce the electrode noise mainly by increasing the surface area of the electrode.

However, the biological noise, which comes from ion-channels of the neuron under monitoring and superposition of neural signals from other neurons located far away from the recording electrodes, have the largest amplitude and little efforts to tackle this most significant noise source has been spent by the researchers.

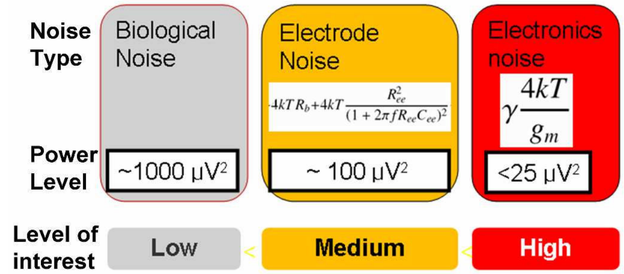


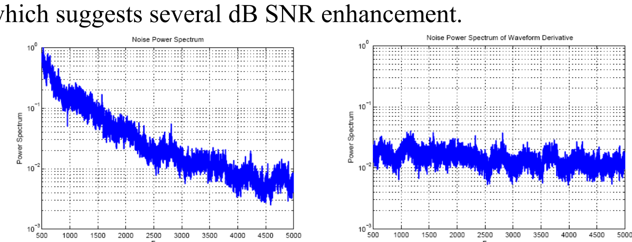
Fig.2 Various noise sources that contribute to the total noise of the recording system.

Noise associated with neural spikes typically has a dominant component at a lower frequency. An example of measured noise spectrum is shown in Fig. 3 (a), which can be curve fitted as

Erreur ! Des objets ne peuvent pas être créés à partir des codes de champs de mise en forme. (1)

,where f_{c1} is the high pass corner frequency of the filter, N_{fc1} is the noise spectrum density at f_{c1}, f is the frequency, α is a decaying constant and N_{therm} is the thermal noise floor.

A noise shaping filter that allocates different gain according to frequency can be used to enhance the overall signal-to-noise-ratio (SNR) given a decaying noise spectrum, as the one shown in Fig. 3(a) [7]. Among different noise shaping filters, a derivative based one that almost linearly emphasizes signal according to frequency can optimally boost the SNR when α =2, which is approximately the case in Fig. 3 (a). After the derivative based noise shaping filter, the noise spectrum is plotted in Fig. 3(b) without changing the scale, which suggests several dB SNR enhancement.



(a) (b)

Fig. 3. Noise spectrum of recordings from an animal object. (a) Noise power spectrum measured from a cat. (b) Noise power spectrum after the derivative based noise shaping filter (the same data in (a) is used). Both (a) and (b) are plotted in the same scale. "x" axis represents the frequency from 500Hz to 5KHz in a linear scale; "y" axis represents the spectrum density in a log scale.

The unique distribution of noise powers from different noise sources provides an insight to optimize the implantable neural interfaces as well. The fact that the biological noise has the largest power among all noise sources implies that the fundamental resolution of the recording system is more affected by the biological noise rather than electronics one. Therefore, there is not much need to push the amplifier design to have an extremely low-noise. Rather it is a better choice to achieve lower power consumption and smaller area by adjusting the target input referred noise of the amplifiers to such a level that the quality of the recorded signal is mainly determined by the biological noise.

B. UWB wireless communication system

Recently, FCC assigned the frequency band from 3.1GHz to 10GHz for low/high data rate wireless personal area network (WPAN) and short-range applications [8]. Its wide bandwidth makes it suitable for the high-density neural recording applications, which produces a data rate of more than 80Mbit/sec from 128 recording channels [9]. Another merit of using UWB in this particular application is that the antenna size can be made very small due to the high-frequency nature of the UWB, making it possible for the system to be miniaturized so that the whole system can be implanted or carried by the biological objects with almost no burden [10].

In our platform, the date rate between the implanted side and central unit that is outside the biological object is asymmetrical unlike other UWB applications. While the data rate of up-link, which transfer significantly large recording data produced by the neural interface, requires a wide bandwidth, the data rate of down-link for the access and control of the neural interface does not need that wide bandwidth. Bandwidth of only a few kbit/sec is enough to control the stimulators and adjust the performance of the recording unit such as gain and bandwidth of the amplifiers. Therefore, although the reported commercial receiver designs of UWB systems have been consuming more power than those of narrow band communications, the receiver on the implanted side can operate on extremely low power consumption by the trade off between power consumption and maximum data rate available.

In this work, impulse radio based UWB (IR-UWB) is employed rather than complex and power consuming orthogonal frequency division multiplexing (OFDM) UWB. In IR-UWB, short pulses are generated for the transmission of data, and both the center frequency and bandwidth of the pulse do not have to be very accurate. This leads to a very simple, small-area, and low-power transmitter design while providing enough data bandwidth for 128-channel neural recording system because of its wideband nature [11].

To implement the multiple access capability in IR-UWB based communication system, a communication protocol is necessary to avoid the collision of the data among multiple biological objects. Although there are many WPAN protocols such as Bluetooth or Zigbee, they are not proper for the implantable neural recording systems due to their complex functionality such as self organizing mesh network capability and complex MAC (Medium Access Control) layer scheme to handle channel contention. Thus it is hard to apply current WPAN protocol such as Bluetooth or Zigbee without any modification to our platform.

In this platform, ID-access based star network scheme, which is popular in RFID applications are employed. ID-access based protocol not only enables the random access of the implanted devices but also can be implemented efficiently because it does not require global clock for the synchronization of each devices to the central unit. Fig. 4 shows the network model of the platform. The network consists of multiple implant units on biological objects and a central unit sharing communication channel at any time. Unlike the conventional sensor networks where sensor nodes transmit data to the base station periodically, the implant unit is required to transmit data only when the central unit requests data. The central unit chooses a target implant unit by broadcasting command frame which contains implant unit ID. In the implant side, all units decode received command frame and the unit with correct ID starts to execute the required task of recording and stimulation.

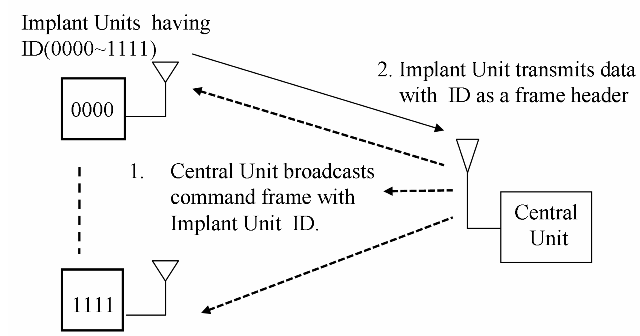


Fig. 4. Network model of the platform.

C. Neural signal processing

As a complementary approach to PCA, spike feature extraction algorithm based on informative sample set was reported in [12] to identify uncorrelated local features. This concept requires only a subset of samples containing the necessary information to cluster the data. Intuitively, a sample is considered to be informative if the superimposed spikes can be classified into multiple clusters by evaluating the sample alone. Combining derivative operation and sample selection, improved sorting performance is observed [12]. As a preliminary implementation to the feature extraction algorithm using informative samples, the height of the original spike waveforms and maximum and minimum values of its first derivatives are used as the features to classify spikes [13]. The choice of this simplified sample set for implementation is based on three reasons. First, it requires small computation and little memory. Second, samples during the fast transition period frequently exhibit high information score [12]. Third, obtaining these three features requires no training.

From the extracted spike features, a clustering algorithm is applied to identify individual neurons, which faces the following challenges. First, the shapes of the clusters can be irregular and unpredictable. Second, the density and size of each cluster vary significantly. Third, the number of data points is limited due to a short data acquisition period and an accurate density estimate is usually not available. Fourth, it is likely that noise and recording artifacts are misidentified as spike events, which further contaminates the density distribution. Fifth, efficiency is critical since the algorithm is preferably to be realized with hardware subjected to power and size limitations. To deal with those challenges, we developed a new clustering algorithm, called evolving mean shift (EMS) algorithm [14] for classifying spike features. EMS gives an objective energy function to characterize the compactness of the data, and through iterations the data points converge into well formed clusters and the associated energy approaches zero. By claiming the isolated modes, EMS performs nonparametric clustering on the extracted features. An example of EMS based clustering is shown in Fig. 5.

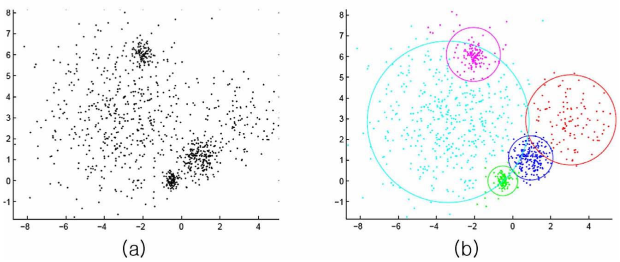


Fig. 5. An example of EMS based clustering. (a) Raw feature space that includes varied cluster density and size. (b) Clustering result generated by EMS

III. Implementation and Test Results

To test the performance of the neural signal processing algorithms, recorded waveform from the cortex of a cat was applied. The identified spike raw waveforms as well as the classified spike band are plotted in Fig. 6. Fig. 6(a) and (c) displays the spike raw waveforms; Fig. 6(b) and (d) displays the classified spike clusters.

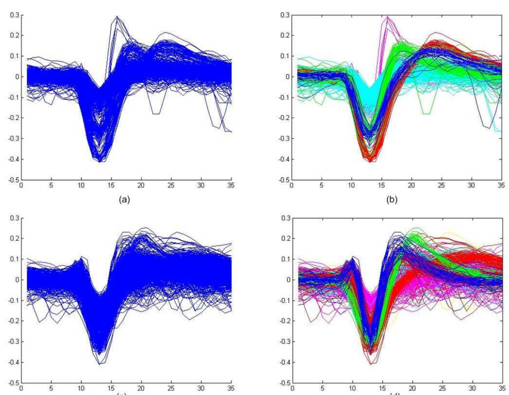


Fig. 6. (a)detected spike events are superimposed and displayed. (b) classified spike clusters. (c) detected spike events are superimposed and displayed. (d) classified spike clusters.

A test system has been implemented to verify the UWB technology of the platform. A 128-channel integrated neural recording IC with UWB telemetry [11] was employed as a core part of the system as shown in Fig. 7. The system was designed to operate on batteries and transmits the recorded data through on-chip UWB telemetry, which achieved the data rate of 90Mbit/sec at the distance of 1m from the receiver, which was implemented using off-the-shelf commercial components.

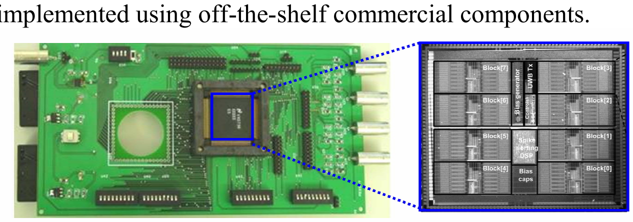


Fig. 7. Photo of the test system to verify the UWB technology for the platform.

IV. Conclusion

A design of versatile platform, which enables the research on high-level brain functions, was presented. Challenging requirements imposed by the unique nature of the application were analyzed and appropriate technical solutions were proposed. IR-UWB based communication system with asymmetrical data rate and ID-access based protocol enables the platform that can support multiple free-running biological objects. Signal processing technique to increase the SNR of the recorded signal, detect spikes, extract features, and classifies were presented as well. Prototype demo system and software were also implemented and key concepts of the technologies are verified by the experimental results. A complete platform is currently under development.

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